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T Pyxidis: The First Cataclysmic Variable with a Collimated Jet

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ABSTRACT

We present the first observational evidence for a collimated jet in a cataclysmic variable system; the recurrent nova T Pyxidis. Optical spectra show bipolar components of H α with velocities ~ 1400 km s $^{-1}$, very similar to those observed in the supersoft X-ray sources and in SS 433. We argue that a key ingredient of the formation of jets in the supersoft X-ray sources and T Pyx (in addition to an accretion disk threaded by a vertical magnetic field), is the presence of nuclear burning on the surface of the white dwarf.

Subject headings: accretion, accretion disks — (stars:) binaries: spectroscopic — stars: individual (T Pyxidis) — (stars:) white dwarfs

1. Introduction

Highly collimated jets have been observed from a wide variety of astrophysical objects. These include: young stellar objects (YSOs), high mass X-ray binaries (HMXBs), black hole X-ray transients, possibly low-mass x-ray binaries (LMXBs) containing a neutron star, symbiotic stars, planetary nebula nuclei (PNN), supersoft X-ray sources (SSS) and of course active galactic nuclei (AGNs) (see e.g. the recent review by Livio 1997 and references therein).

An examination of the above list reveals immediately that all the systems in which jets have been observed include accreting central objects. This has led to the generally accepted paradigm, in which jets are formed (namely, are accelerated and collimated) by accretion

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disks, which are threaded by a reasonably ordered, large scale magnetic field (e.g. Königl 1986; Blandford 1993; Pringle 1993; Livio 1997). Conspicuously absent in the above list, are cataclysmic variables (CVs), even though they contain the best studied accretion disks (see e.g. Warner 1995). In fact, winds and very poorly collimated outflows have been observed from CV disks (e.g Drew 1995; Knigge, Woods & Drew 1996; Shlosman, Vitello & Mauche 1996), but never a collimated jet. It is unclear at present whether the fact that jets have not been observed in CVs until now, merely represents an observational difficulty (e.g. that there isn't enough material around CVs for the jets to interact with, and hence become visible), or that CVs indeed cannot produce jets.

In this letter we present the first observational evidence for a collimated jet in the recurrent nova T Pyxidis. The observations and results are presented in Sections 2 and 3, and their implications for jet formation mechanisms are discussed in Section 4.

2. Observations and data reduction

We obtained intermediate resolution spectra of T Pyx and U Sco in 1996 and 1997 using the 3.9-m Anglo-Australian Telescope at Siding Spring, Australia. The T Pyx spectra were taken in January 1996, 1997 and the U Sco spectra were taken in June 1996. A Tek 1024² CCD attached to the RGO spectrograph was used during all the observing runs. The spectral resolution was 1.3Å (FWHM=60 km s⁻¹ at H α) for the 1200B/V grating and 3Å (FWHM=192 km s⁻¹ at H β) for the 600B grating. Cu-Ar arc spectra were taken during the observations at regular intervals for calibration of the wavelength scale, in addition to a series of tungsten flat-fields and bias frames. Further observational details are given in Table 1.

The data reduction was performed using the Starlink FIGARO package and PAMELA routines of K. Horne. The bias level was removed from each frame by using the mean overscan regions and then flat-fielded using the observed tungsten lamp. One-dimensional spectra were extracted using the optimal algorithm of Horne (1986), and calibration of the wavelength scale was achieved using the MOLLY package of T. R. Marsh.

3. Results and analysis

In Fig.1 we show the variance-weighted average of the T Pyx spectra taken during the two observing runs. The strong H α and He I emission lines are doubled-peaked and have broad bases (FWZI \sim 1500 km s⁻¹). We are also able to identify additional emission

components which we have marked as S^- and S^+ (following the nomenclature of Crampton et al. 1996). The wavelengths and relative velocities of the S^+ and S^- features as measured from the average spectra in Fig. 1 are listed in Table 2.

These spectral features have also been seen in the supersoft X-ray sources (Crampton et al. 1996; Southwell et al. 1996), which are binary systems in which a white dwarf accretes from a subgiant companion at such a high rate that it burns hydrogen steadily at its surface (van den Heuvel et al. 1992; Rappaport et al. 1994) and in the prototype jet source SS 433 (Margon 1984; Vermeulen 1993). By drawing the analogy of T Pyx with the SSS we speculate that the observed bipolar features may be produced by the same mechanism as in the SSS.

4. Discussion

4.1. The binary inclination of T Pyx

The inclination angle of T Pyx is not known. In the following we estimate lower and upper limits to the inclination. Various authors have pointed out that the double-peaked emission line profiles can be interpreted as arising from an accretion disk viewed at high inclination. However, it should be noted that a double-peaked emission line profile can also arise from a system with an inclination as low as 15° (see the models of Horne & Marsh 1986).

Assuming that the double-peaked lines arise entirely from the disk, we can estimate the binary inclination i of T Pyx by measuring the separation of the $H\alpha$ emission-line peaks.

The Keplerian velocity of the outer edge of the disk (v_d) is given by $v_d = (GM_1/R_d)^{0.5}$. Combining this with Kepler's third law, Paczynski's (1971) formula for the Roche lobe radius, and the assumption that the accretion disk fills about 70 per cent of the white dwarf's Roche-lobe, gives $v_d = 1081(M_1/P_{hr})^{1/3}$ km s $^{-1}$, where M_1 is the mass of the white dwarf (in solar masses), and P_{hr} is the orbital period (in hours). The separations of the $H\alpha$ emission-line peaks measured from the average 1996 and 1997 spectra of T Pyx are 202 ± 6 km s $^{-1}$ and 180 ± 17 km s $^{-1}$ respectively, implying a projected velocity of the outer edge of the accretion disk of $v_d \sin i \sim 100$ km s $^{-1}$. Using the above formula with $P_{hr}=1.84$ hrs (Schafer et al. 1992) and $M_1 \sim 1.2M_\odot$ (as required for a recurrent nova, e.g. Webbink et al. 1987) gives a binary inclination of $\sim 6^\circ$. This should clearly be regarded as a lower limit to the binary inclination, since for very low inclinations thermal broadening in the disc may dominate the velocity distribution.

We can attempt to estimate the inclination angle also using the observed outflow velocity (a similar procedure is often applied to YSOs, e.g. Hirth, Mundt & Solf 1994).

Typically, outflows from CVs are observed to have velocities in the range 3000-5000 km s⁻¹ (e.g. Drew 1995; these are of the order of the escape velocity from the central object, e.g. Livio 1997). Taking the observed velocity of 1380 Km/s (Table 2), and an average jet velocity of 4000 km s⁻¹, we obtain $i \sim \cos^{-1}(V_{obs}/V_{jet}) \sim 70^\circ$. This should be regarded as an upper limit since the system is non-eclipsing.

4.2. Should CVs have jets?

While it is not absolutely clear if the apparent absence of jets in CVs is merely a consequence of observational difficulties (see Introduction), suggestions have been made that jets cannot form in CVs (Spruit 1996). This idea is based on the properties of one of the mechanisms suggested for jet collimation; poloidal collimation. In this mechanism, the disk is threaded by a vertical magnetic field which is strongest at the disk center, but which has its largest flux in the outer disk. The vertical outflow from the disk diverges at first, but as it encounters the strong magnetic flux at the outer disk it is collimated (see Blandford 1993, Spruit 1994, Ostriker 1997; Spruit et al. 1997). Good collimation is obtained if the disk radius is of the order of the Alfvén radius (Konigl & Kartje 1994; Spruit 1996; Ostriker 1997). For such a collimating configuration, the minimum opening angle of the jet is given by: $\theta_{min} \sim (R_{in}/R_{out})^{0.5}$, where R_{in} and R_{out} are the inner and the outer disk radii respectively. An examination of the expected opening angles for all the astrophysical objects which produce jets (Spruit 1996; Livio 1997) reveals that whilst collimated jets are expected in AGNs, YSOs, HMXBs, and black hole X-ray transients, they are not expected in CVs, due to the relatively large ratio of R_{in}/R_{out} . However, as was pointed out by Livio (1997), the same argument suggests that jets would not have been expected in SSS and in PNNs, and yet these two classes of objects do exhibit collimated jets (Pakull 1994; Crampton et al. 1996; Southwell et al. 1996; Harrington & Borkowski 1994; Trammell & Goodrich 1996; Pollacco & Bell 1996). For example, the opening angle expected in the SSS RXJ 0513-69 is only smaller by a factor ~ 1.5 than that expected for a CV system with a 5 hr orbital period. The argument based on poloidal collimation cannot therefore represent the complete picture.

Recently, it has been speculated that in order to produce *powerful* jets, it is necessary to have, in addition to an accretion disk threaded by a magnetic field, an energy/wind source associated with the central object (Livio 1997). Livio then went on to identify this additional energy source in every class of objects which are observed to produce jets. In the case of the SSS and the PNNs, this additional source was suggested to be nuclear burning on the surface of the white dwarf. It is important to emphasize that the magnetized disk is

still the key ingredient for the acceleration and the collimation of the jet, with the central source merely providing the extra bit of energy required to ensure the existence of a solution with the desired properties (e.g. Ogilvie 1997). According to this speculation, CVs would *normally* not produce powerful jets since they have no such additional source (no nuclear burning, no boundary layer, no supercritical accretion; see Livio 1997 for a discussion).

4.3. The case for jets in T Pyx

Recurrent novae are cataclysmic variables observed to repeat nova eruptions on a time scale of less than a century or so. T Pyx is unusual. Its outbursts are very much like those of a slow nova (non violent), whereas all other RNe have very fast nova outbursts. It has the shortest orbital period (1.84 hr; Schaefer 1990) and in quiescence it has extremely blue colours arising from a hot component. It is the nature of the hot component which led Webbink et al. (1987) to suggest that nuclear burning on the surface of the white dwarf was still taking place. In this case the white dwarf would be very hot and so the thermonuclear runaway would occur under not so degenerate conditions. This would lead to the outburst being non-violent and slow, as is observed. A hot accretion disk would not be sufficient to explain this property, (it should be noted though that one could also explain the slow outburst in T Pyx if the mass of the white dwarf was somewhat smaller than in the other RNe where it is believed to be close to the Chandrasekhar limit; Webbink et al. 1987). Therefore T Pyx may be the only CV in which nuclear burning on the surface of the white dwarf is ongoing in quiescence. The detection of jets from this system would therefore be consistent with Livio's (1997) speculation, i.e. the comparison of nuclear burning RNe with the SSS.

Our optical spectra of T Pyx show features (marked S⁺ and S⁻ in Fig. 1) which we interpret as high velocity components of H α , whose origin is in some type of bipolar outflow, similar to that observed in the SSS. If our interpretation of these features and the analogy to the SSS is correct, then T Pyx may be the first CV that shows collimated jets. Because of the uncertainty in the inclination angle, it is impossible at present to determine the degree of collimation. If we assume that the entire width of the S features is due to finite collimation (rather than to a spread in the velocity) and that the outflow consists of a uniformly filled cone, then we obtain an opening angle of 4.2° for $i = 70^\circ$, but very poor collimation for $i = 6^\circ$. (The opening angle is approximately given by $\sin^{-1} \Delta V/(V \tan i)$, where $\Delta V/V$ is the range in line-of-sight velocity of the S-features with respect to the mean velocity, i.e. 20 percent; see Fig 1).

4.4. U Sco

An interesting test for the above scenario can be provided by another recurrent nova, U Sco. According to our present understanding of recurrent novae, the frequency of the outbursts can be understood in terms of extremely high accretion rates ($\gtrsim 10^{-8} M_{\odot} \text{ yr}^{-1}$) onto massive white dwarfs ($\gtrsim 1.2 M_{\odot}$; see Webbink et al. 1987 and Prialnik & Kovetz 1995). Therefore, the accretion rates in T Pyx and U Sco should be comparable (since they have a very similar outburst frequency). In U Sco, however, nuclear burning is probably not taking place in quiescence, since the outbursts are very violent, indicating a thermonuclear runaway under very degenerate conditions (which would not have been the case if nuclear burning were to continue in quiescence). Our spectroscopic observations (see section 2) show that powerful jets are indeed not observed in U Sco (see Fig 2), again in agreement with the need for an energy source associated with the central object. However, this could be an observational selection effect, since the system is eclipsing (Schaefer 1992), and therefore highly Doppler-shifted components may not be observable.

4.5. Comparing T Pyx with the supersoft sources

Although the observations show bipolar outflows from T Pyx and the SSSs, and there is evidence for ongoing nuclear burning on the surface of the white dwarf in both cases, the physical environment under which this happens is different for the two objects. The mass accretion rate in T Pyx is a factor of 10-100 less than in the SSS, this implies that the nuclear burning is not steady (Nomoto 1982). Rather, T Pyx experiences nova outbursts, with episodes of continued burning after the outbursts. This is not the case in the SSS, where the high mass accretion rates are sufficient for the white dwarf to burn steadily. Another similarity between T Pyx and RXJ0513-69 is in the fact that there are strong indications that the WD in the latter system is also fairly massive (Southwell et al. 1996).

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Table 1. Journal of observations.

Object	Date	Exposure time	Grating	Dispersion ($\text{\AA} \text{ pixel}^{-1}$)
T Pyx	17/1/1996	$1 \times 900\text{s}$	1200V	0.79
	5/1/1997	$10 \times 200\text{s}$	1200V	0.79
	5/1/1997	$5 \times 200\text{s}$	1200V	0.79
U Sco	21/6/1996	$2 \times 1800\text{s}$	1200B	0.79
	21/6/1996	$3 \times 1200\text{s}$	600B	1.55

Table 2. Properties of the $\text{H}\alpha$ Doppler-shifted components in T Pyx.

Year	S^- (\AA)	S^- (km s^{-1})	S^+ (\AA)	S^+ (km s^{-1})
1996	-	-	6593	1380
1997	6539	-1082	6593	1380

Fig. 1.— Average red spectrum of T Pyx taken in 1996 and 1997 with a signal-to-noise ratio of ~ 20 and 25 respectively. The principal H α and He I (6678 Å) emission features are marked, along with the Doppler-shifted components of H α labelled S $^+$ and S $^-$. The spectra have been normalised to the continuum and have been shifted vertically for clarity. The inset shows a close-up of the H α double-peaked emission line taken from the averaged 1997 spectrum.

Fig. 2.— Average blue spectrum of U Sco with a signal-to-noise ratio of about 25 in the continuum. The He II (4541 Å), He II (4686 Å) and H β (4861 Å) emission features are marked. No discernable Doppler-shifted components can be seen.